Multiturn Extraction Using Adiabatic Capture in Islands of Transverse Phase Space: Theoretical Predictions and Preliminary Measurements Results

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and

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Summary

- Motivations.
- Present Continuous Transfer.
- Adiabatic trapping in stable islands.
- Phase space reconstruction.
- Non linear chromaticity measurements.
- Experimental tests of adiabatic trapping.
- Conclusions and outlook.

Motivations

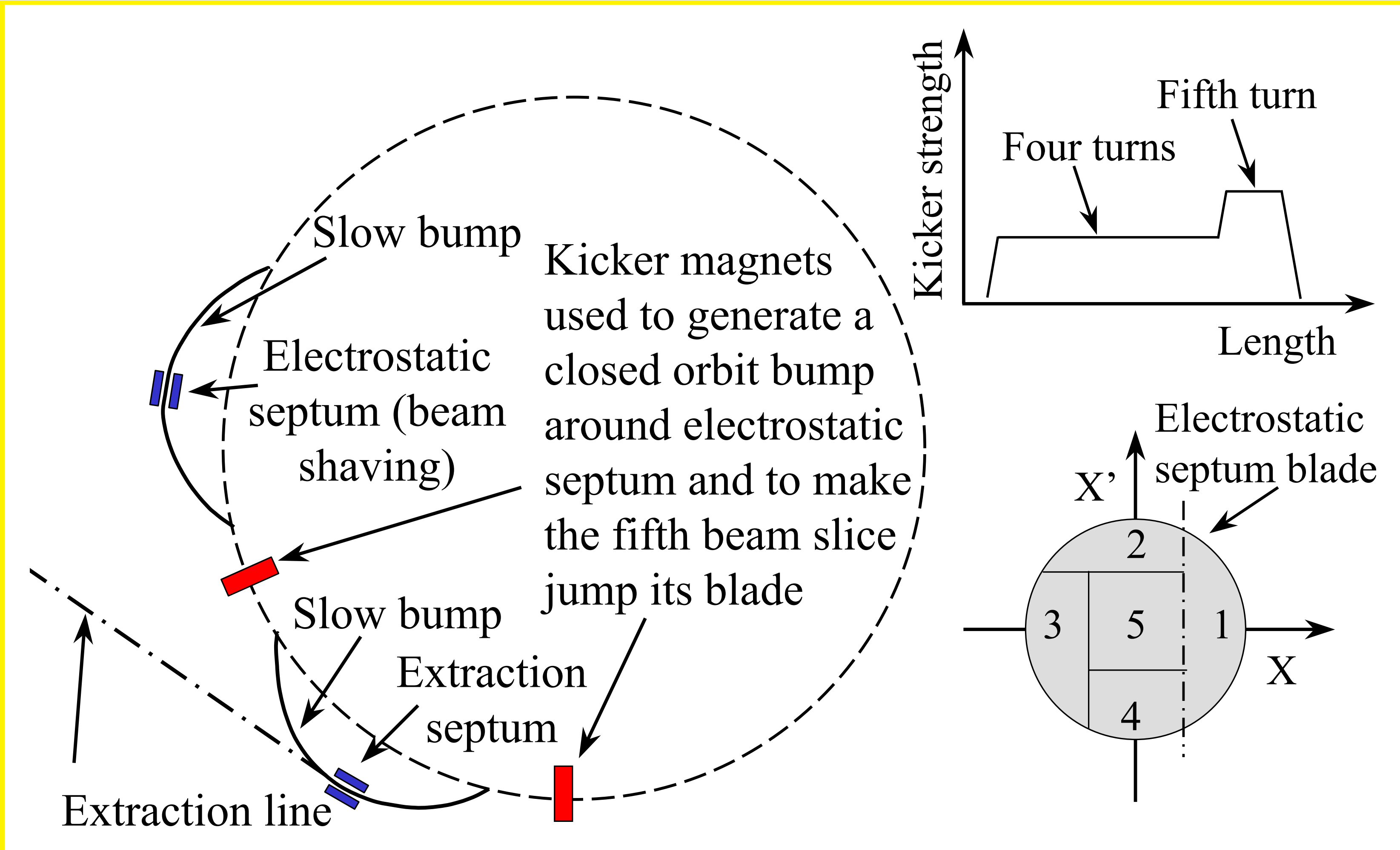
- **Multi-turn extraction** is meant to be an **intermediate mode** between **fast** (one turn) and **slow** (between hundreds to some billions turns).

- **Multi-turn extraction** is meant to **modify the extracted beam emittance** so to overcome aperture limitations in the receiving machine.

- Example: CERN PS multi-turn extraction towards the SPS.
  - The following relation holds $C_{SPS} = 11 C_{PS}$, hence **10** fast extracted pulses from the PS are needed to fill the SPS. This creates problems due to **transient phenomena** and **filling-time**.
  - **A vertical aperture limitation** affects the SPS machine (critical for **high-intensity beams**).
  - The solution found consists in **slicing** the beam so to fill the $5/11$**th** of the SPS machine each PS extraction. This reduces also the **horizontal emittance** (**a phase exchange section is used in the transfer line to transfer the horizontal (vertical) emittance to the vertical (horizontal) plane**)

Present Continuous Transfer

The principle of the present version of the **Continuous Transfer (CT)** is shown here.

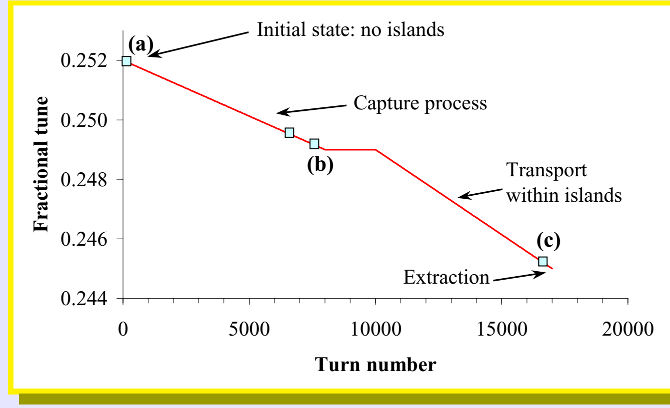


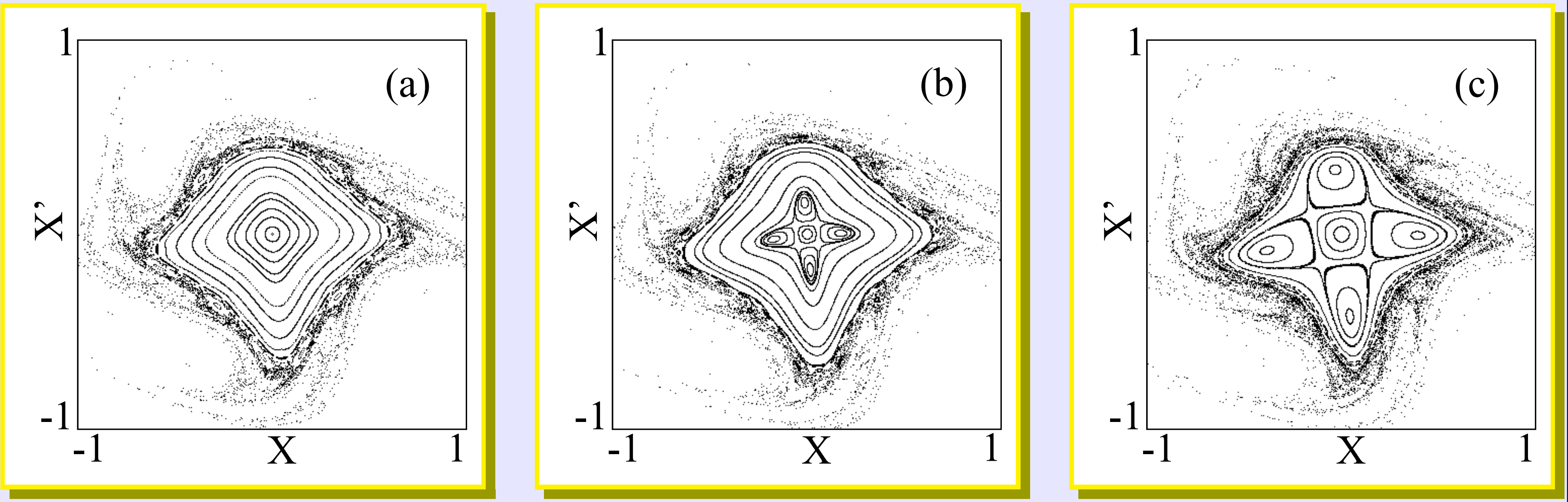
Adiabatic trapping in stable islands

The main ingredients are:

- **Nonlinear elements** (sextupoles, octupoles) to generate **stable islands** in transverse phase space.
- **Tune-variation** to sweep through the resonance, hence breaking the **invariance of the separatrix**.

This approach may be used to generate separate **beamlets** without any **intercepting device**.





Model for numerical simulations

The model for numerical simulations consists of:

- **Localised sextupole and octupole** represented as a **single kick**.
- The remaining part of the ring is assumed to be **linear**.
- The system is **time-dependent** through the **tune**.
- The **vertical motion** is **neglected**.

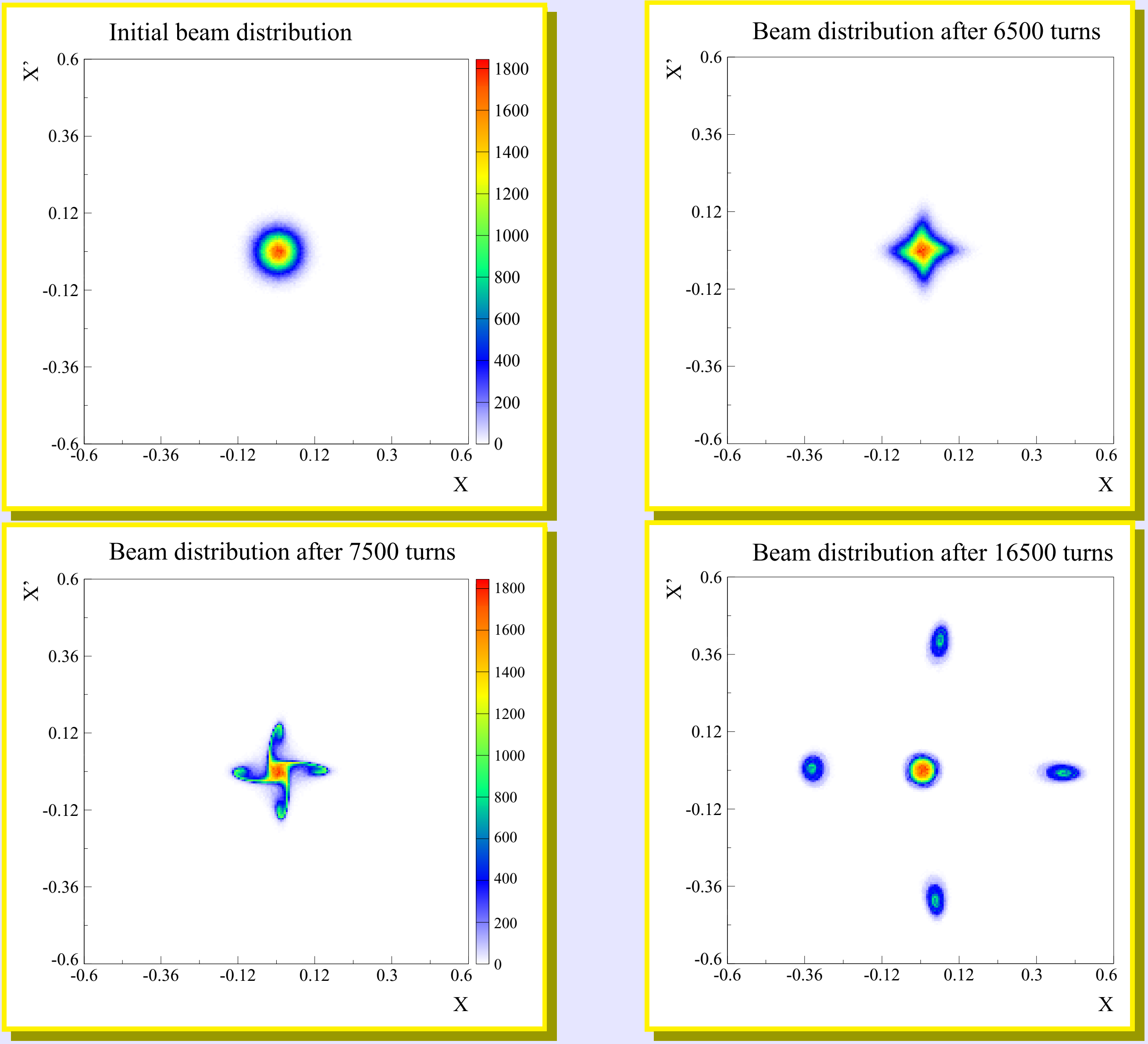
The resulting one-turn map is a **Hénon-like** map

$$\begin{pmatrix} \hat{X}_{n+1} \\ \hat{X}'_{n+1} \end{pmatrix} = R(2\,\pi\,\nu_n) \begin{pmatrix} \hat{X}_n \\ \hat{X}'_n + \hat{X}_n^2 + \kappa\,\hat{X}_n^3 \end{pmatrix}, \quad \kappa = \frac{2}{3}\,\frac{K_3}{\beta_H\;{K_2}^2}$$

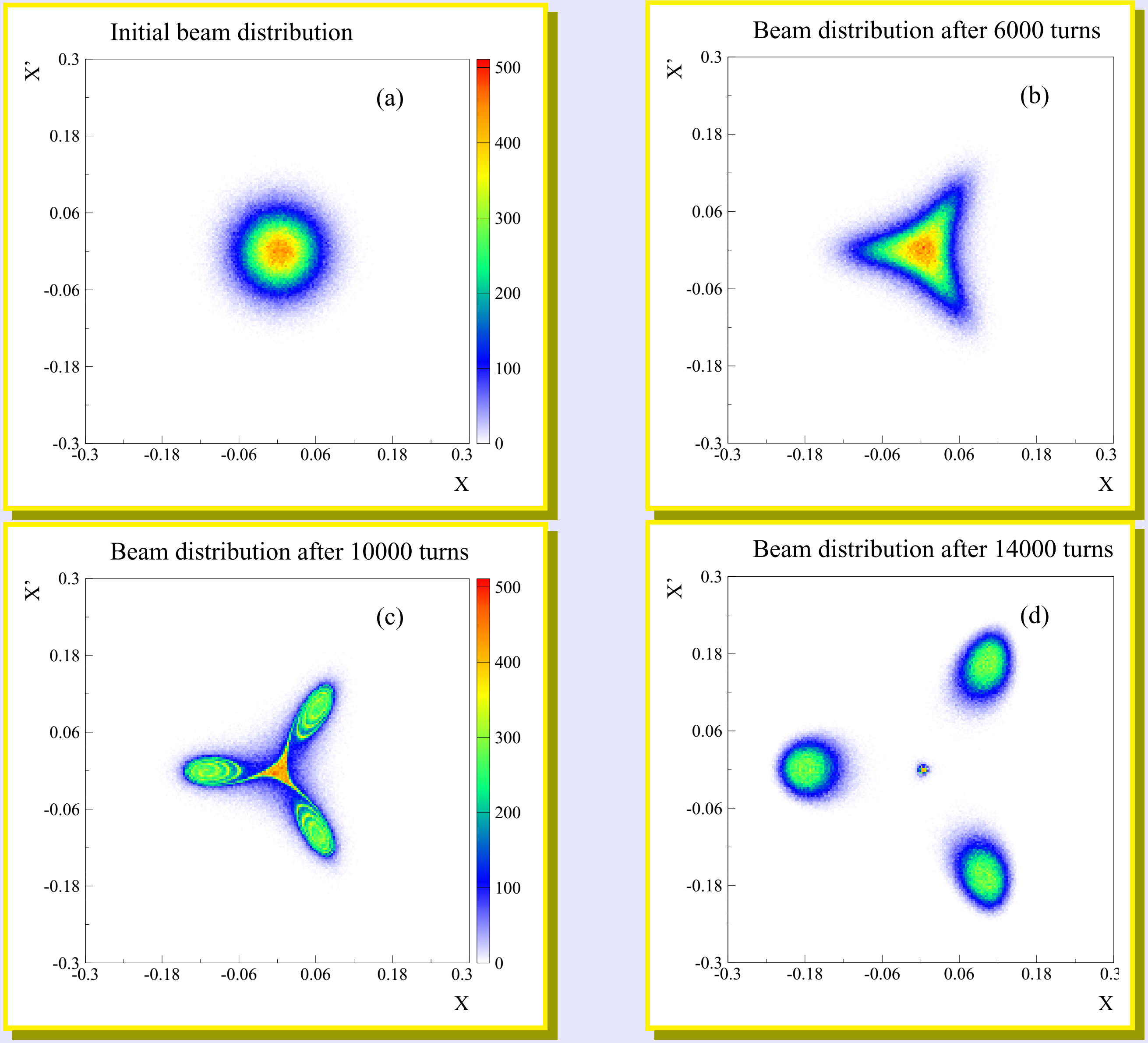
The co-ordinate system $(\hat{X}, \hat{X}')$ is obtained by rescaling the normalised co-ordinates $(\hat{x}, \hat{x}')$

$$(\hat{X}, \hat{X}') = \frac{1}{2}\,K_2\,\beta_H^{3/2}\;(\hat{x}, \hat{x}')$$

Numerical simulations: fourth-order resonance

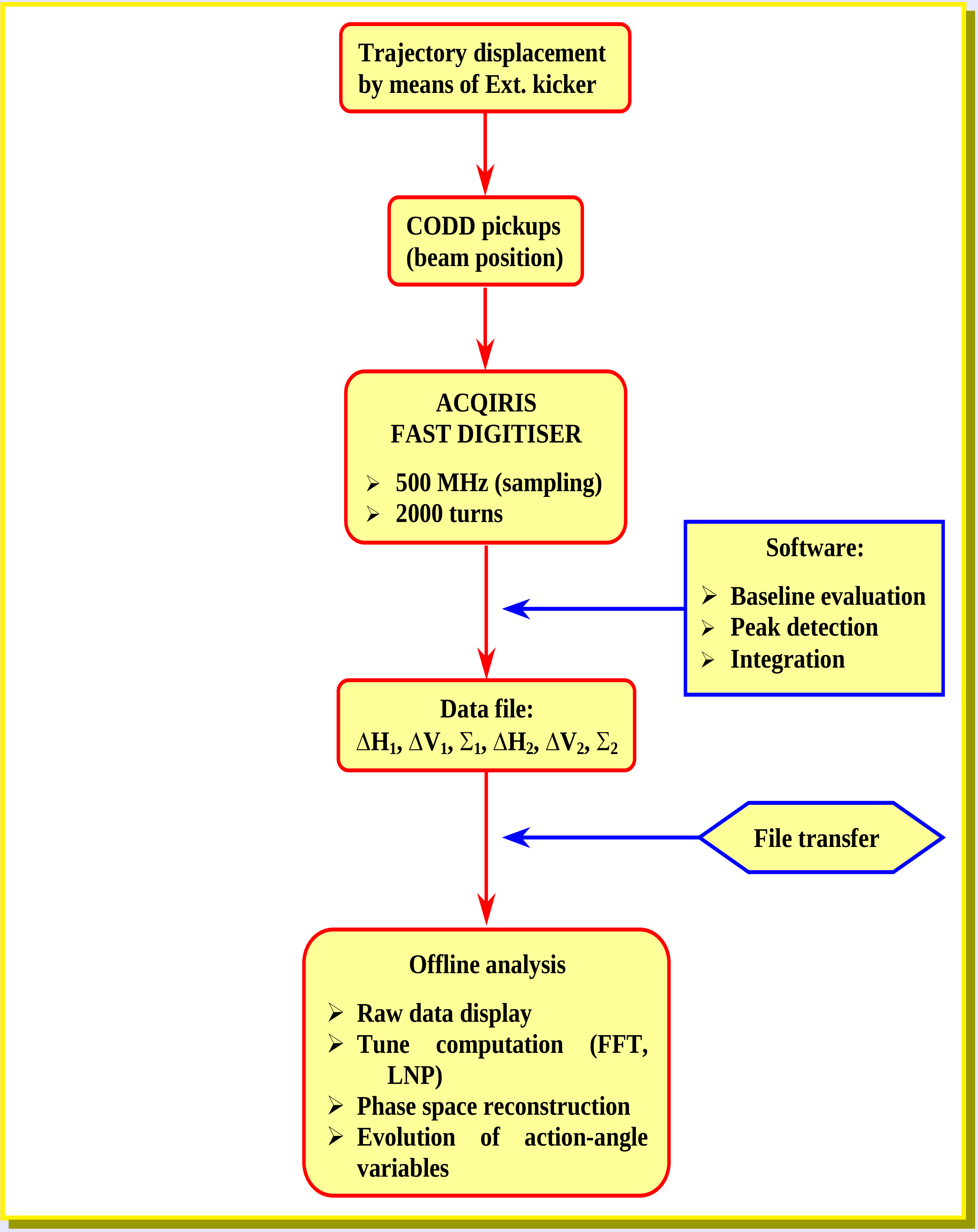


Numerical simulations: third-order resonance

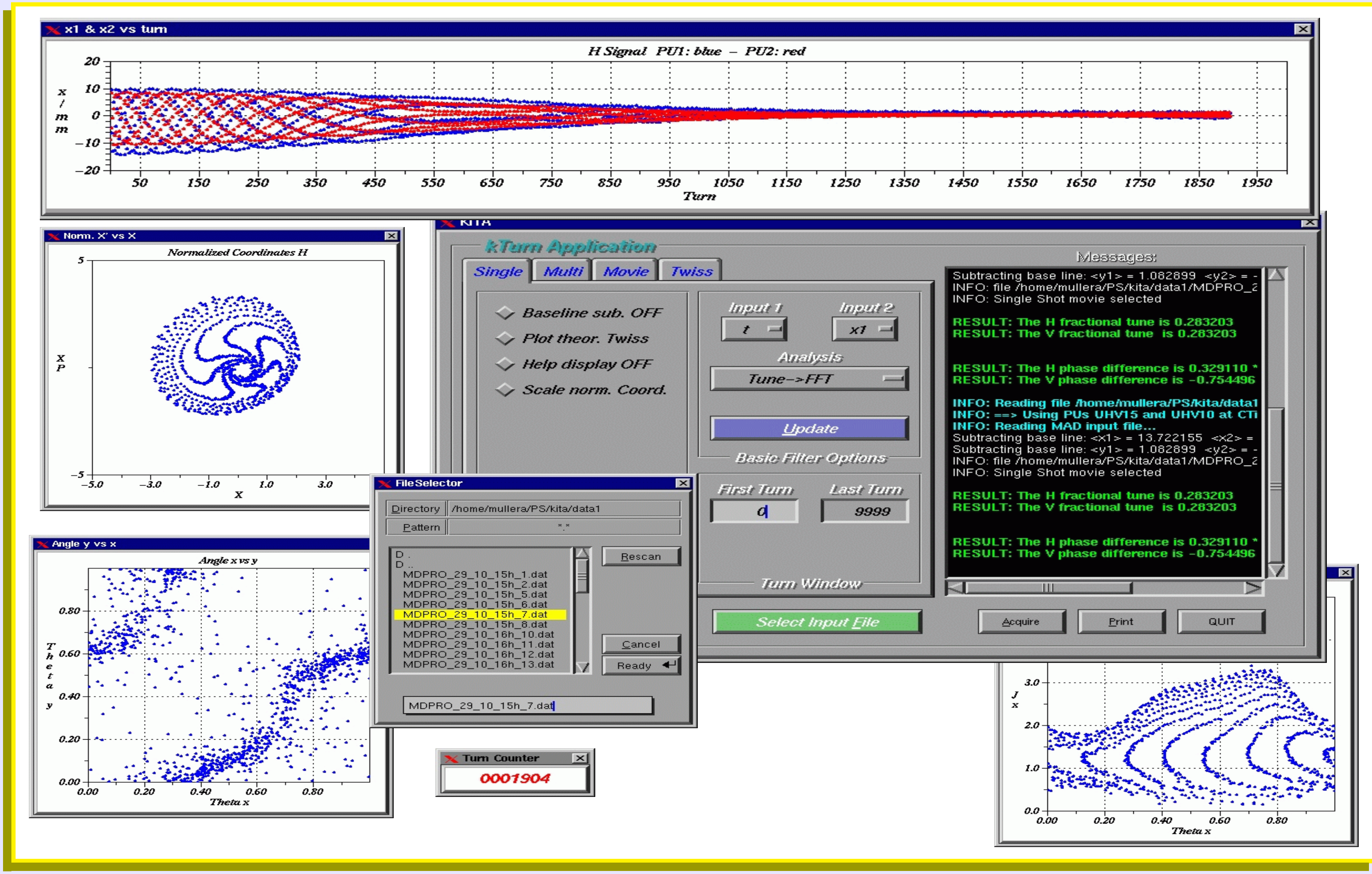


Acquisition and visualisation

A block-diagram of the **acquisition system** together with the **off-line analysis** part is given below:



Visualisation program: an example



Experimental studies

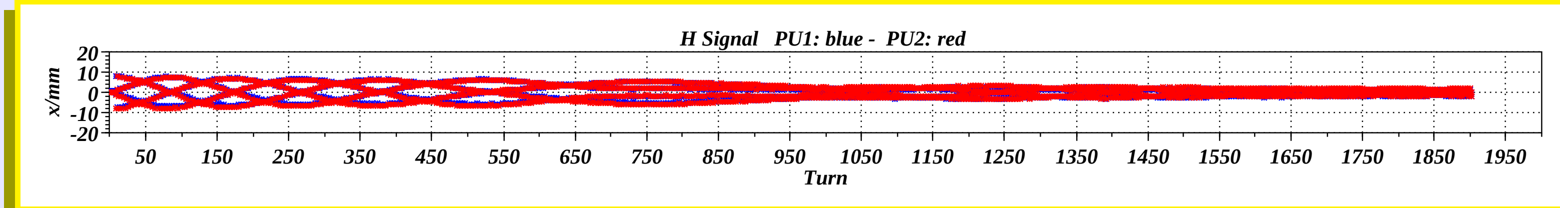
- Phase space measurements with new sextupoles and octupoles.
- Beam characteristics:
  - Single bunch.
  - $N_b \approx 6 \times 10^{11}$ p/b.
  - $\epsilon^*_H \approx 2\ \mu$m, $\epsilon^*_V \approx 1.5\ \mu$m.
  - $\Delta p/p \approx 1.5 \times 10^{-3}$.

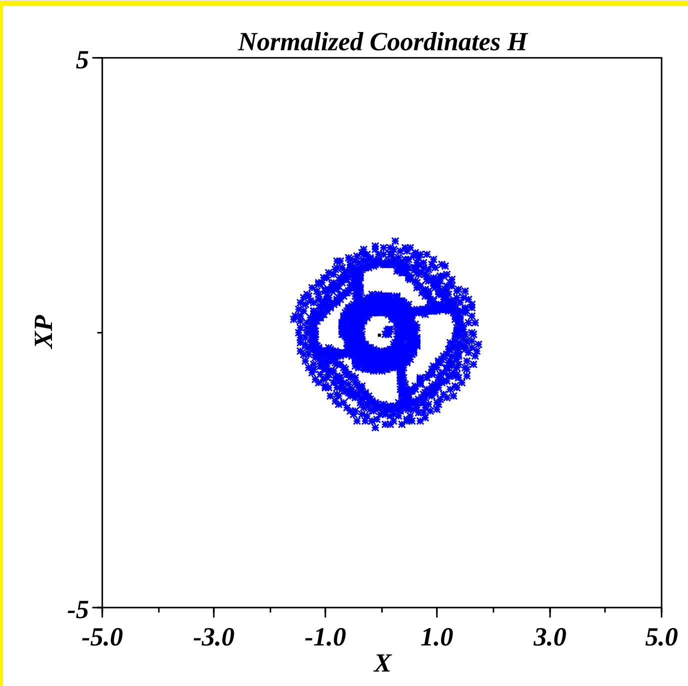
Experimental settings

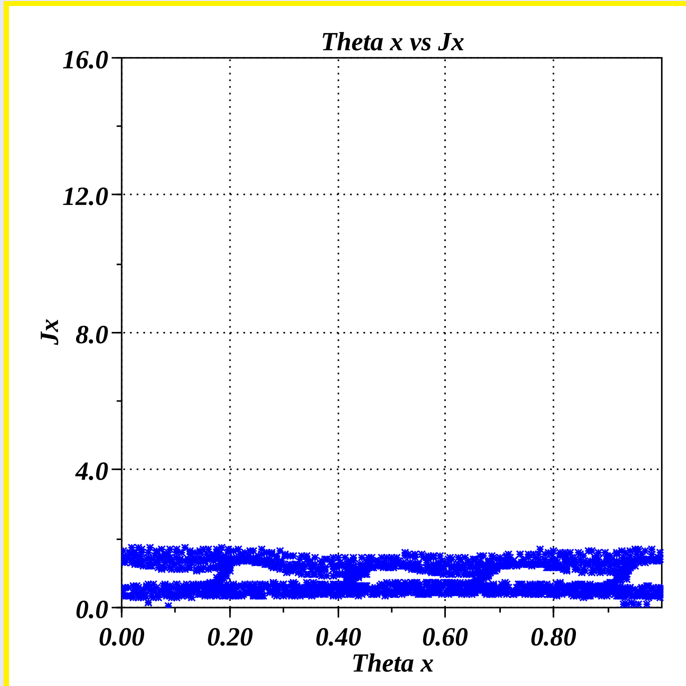
- The Quadrupole for Slow Extraction (**QSE**) is used to change the tune.
- **Results**:No clear signature of islands.
- **Possible explanation**: wrong phase between islands and kicker and/or coupling long./transv. planes.

Preliminary experimental results I

PU 63/67; $V_{kicker} = 80$ kV; $I_{QSE} = -20$ A; $I_{XCT} = 350$ A; $I_{OCT} = 690$ A;

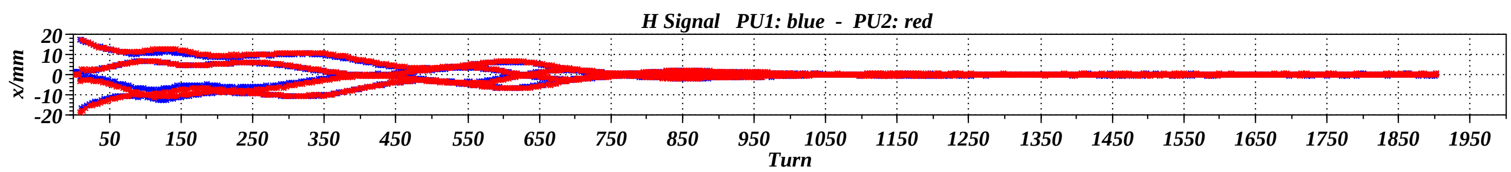


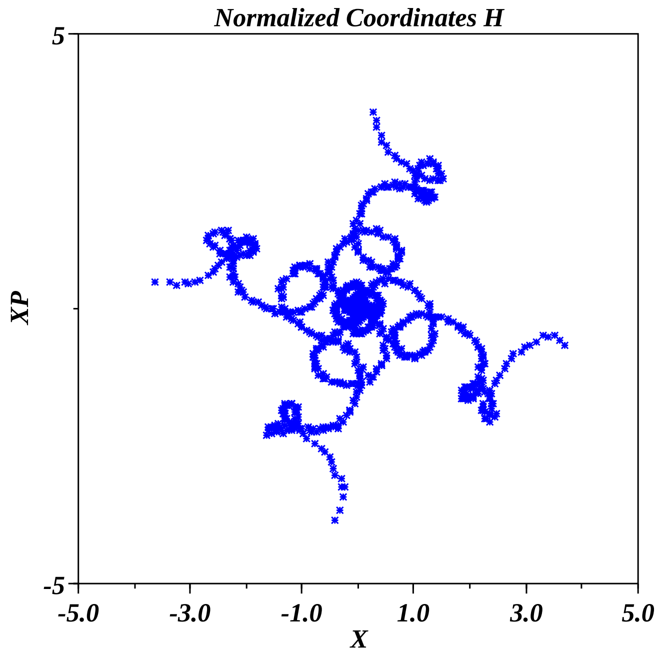


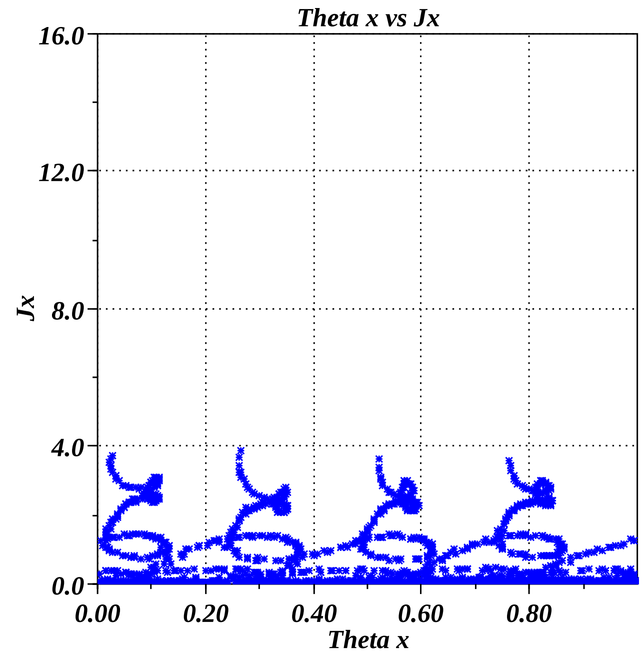


Preliminary experimental results II

PU 63/67; $V_{kicker} = 247$ kV; $I_{QSE} = -20$ A; $I_{XCT} = 350$ A; $I_{OCT} = 690$ A;



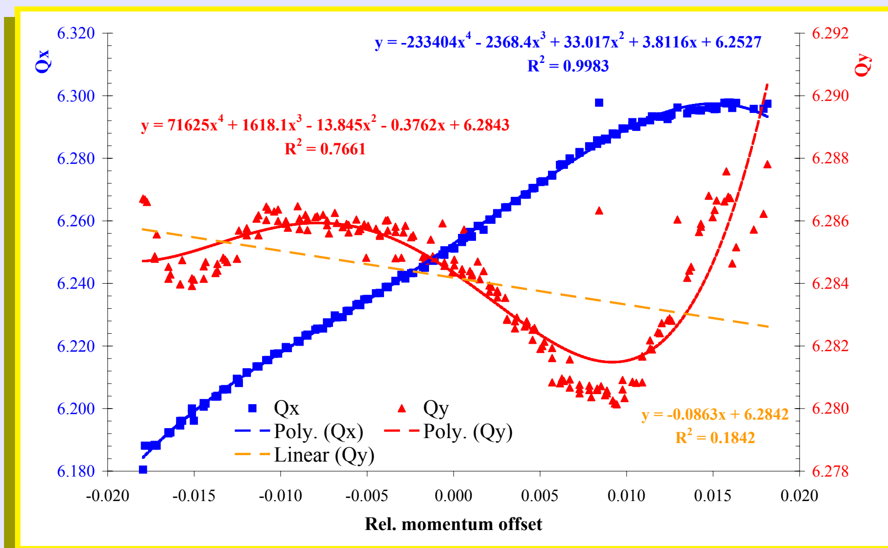


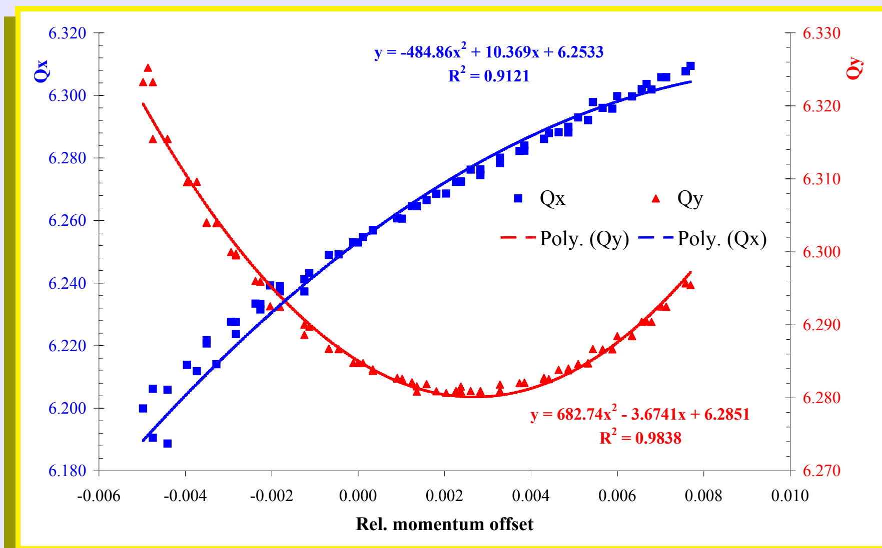


Nonlinear chromaticity

- Standard technique: radial steering + tune measurement.
- Results: $\xi_H \approx 1.5$!
- NB: Contributions from α_1, α_2 in the computation of $\Delta p/p$ (for large values of momentum deviation) are presently neglected.

$I_{QSE} = -15$ A; $I_{XCT} = 0$ A; $I_{OCT} = 0$ A;	$I_{QSE} = -15$ A; $I_{XCT} = -350$ A; $I_{OCT} = 690$ A;

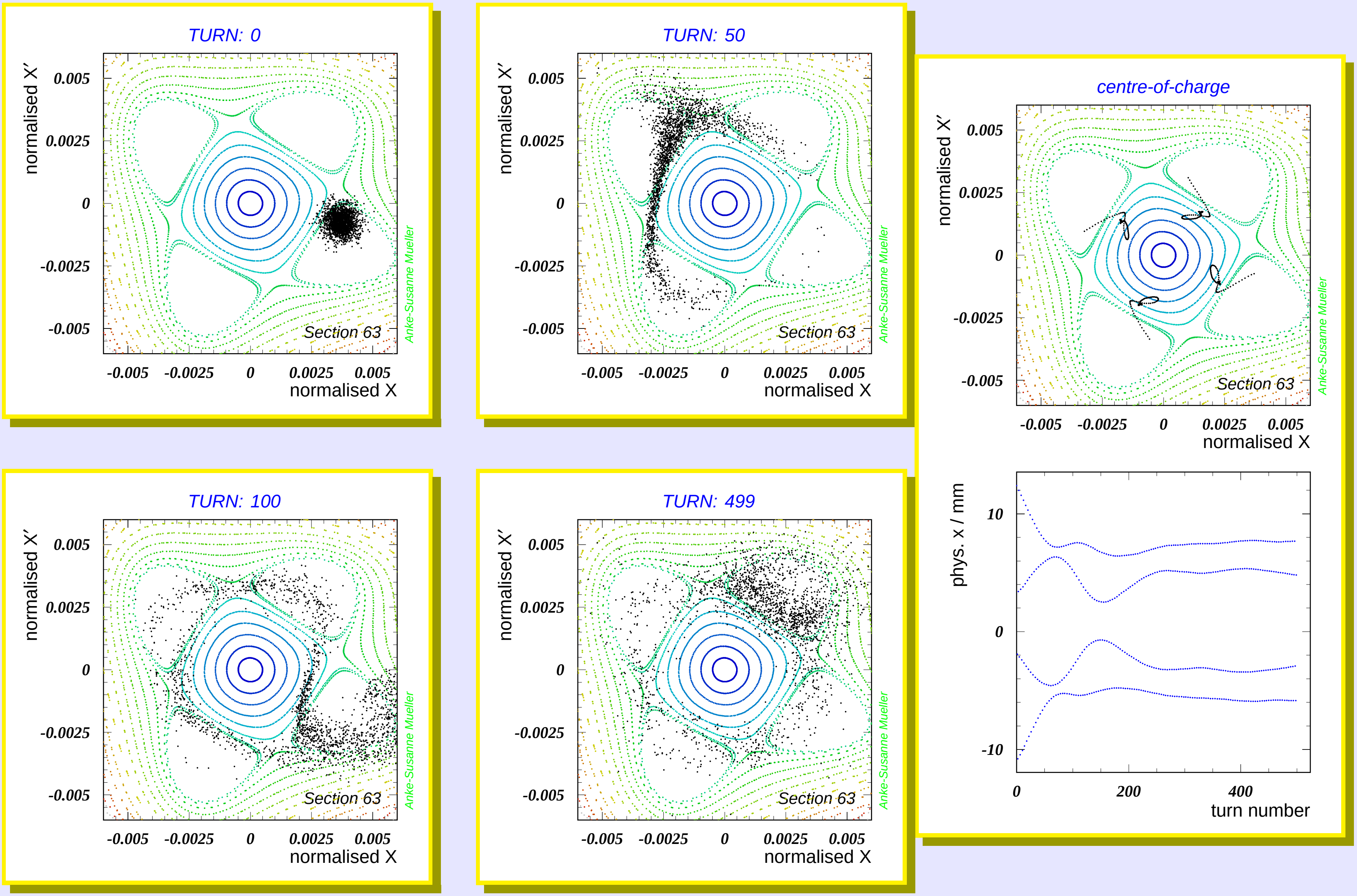




PS model

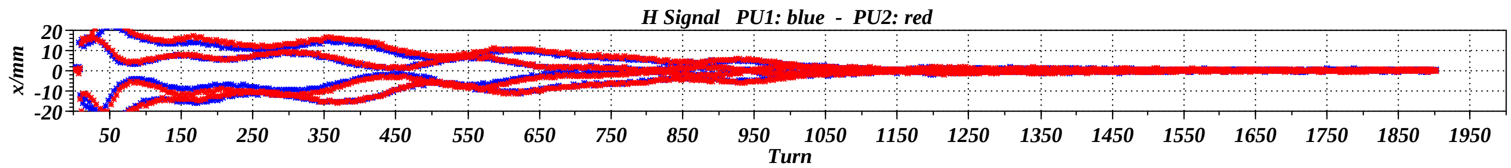
- Using the data from the nonlinear chromaticity measurements a realistic PS model has been setup.
- **Virtual nonlinear kicks** (quadrupoles, sextupoles, octupoles) have been added to each end of the main dipoles. Their strength have been used to **fit** experimental data.
- **Results:**
  - **Very good agreement** between model/measured data (**nonlinear chromaticity**, and **tune vs. QSE strength**).
  - **Good agreement** between measured phase space and numerical simulations based on the new model.
  - **However**: the phase between kicker and islands is not the optimal one (**injection kicker KFA45** would have the right phase, but it is too weak at **14 GeV/c**).
- **Actions:**
  - **Reduce coupling** between long./transv. planes (**reduce rf-voltage in PS**, and **reduce long. emittance in PSB**).
  - **Double kick** the beam (with one-turn delay) to scan along a different direction than the vertical. However, hardware limitations impose: **three turns** minimum delay, **equal amplitude** for the two kicks (hence the scan is possible only along the diagonal).

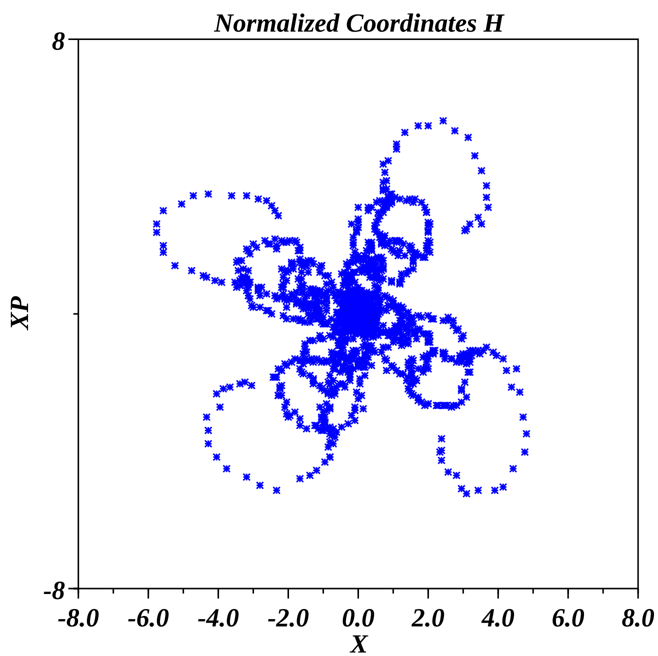
Numerical simulations of preliminary experimental results

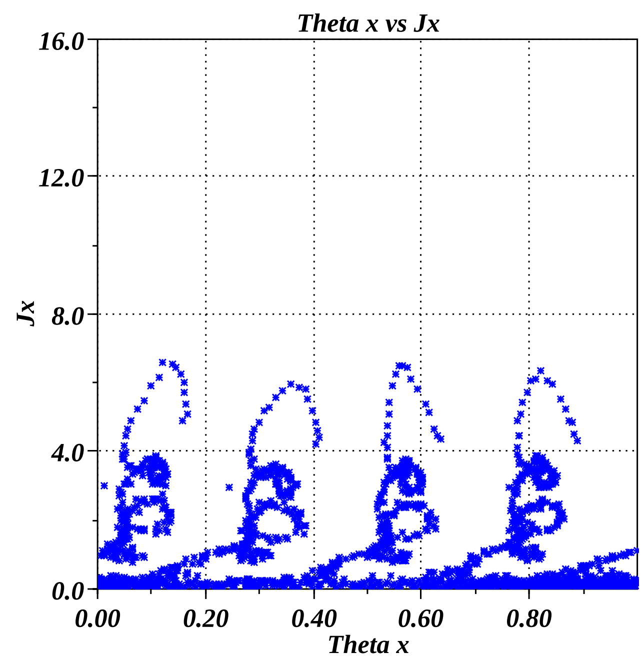


Measurements with reduced long./transv. coupling I

PU 63/67; $V_{kicker} = 187$ kV; $I_{QSE} = -20$ A; $I_{XCT} = 350$ A; $I_{OCT} = 690$ A;

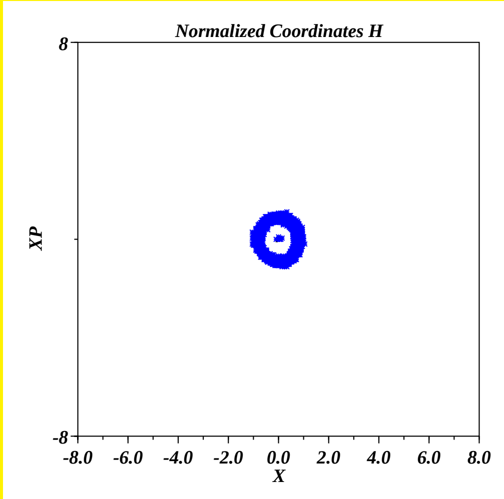




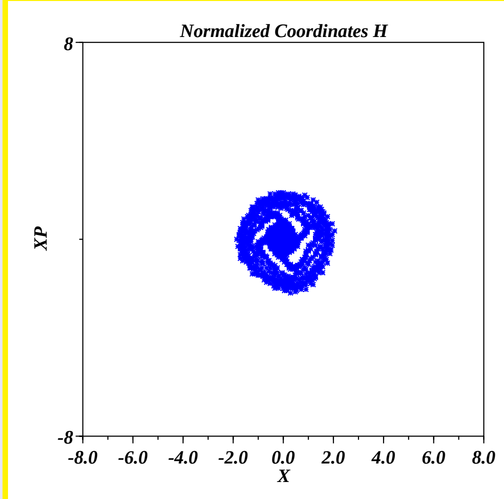


Measurements with reduced long./transv. coupling II

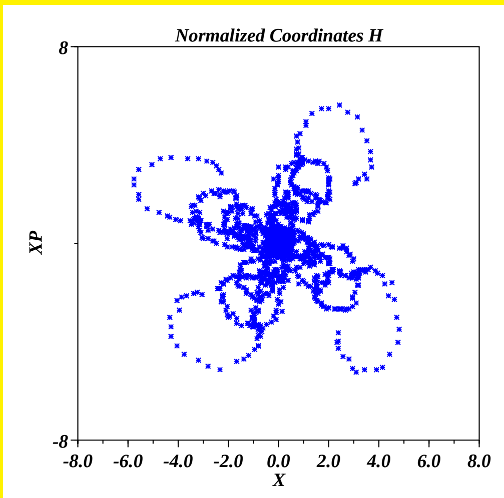
$V_{KFA71} = 45$ kV;



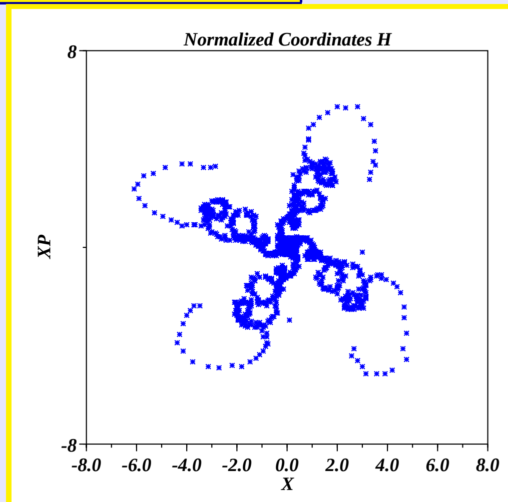
$V_{KFA71} = 65$ kV;



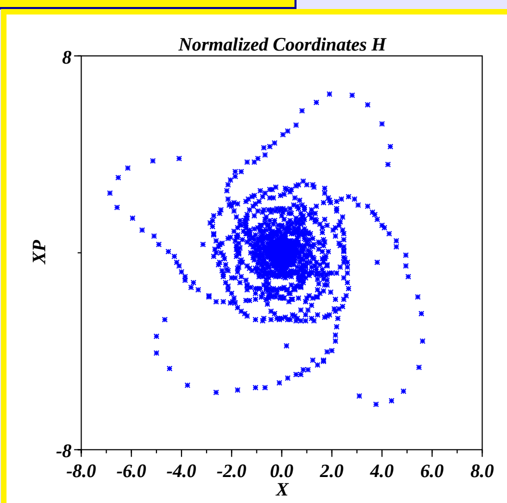
$V_{KFA71} = 184$ kV;



$V_{KFA71} = 204$ kV;



$V_{KFA71} = 236$ kV;

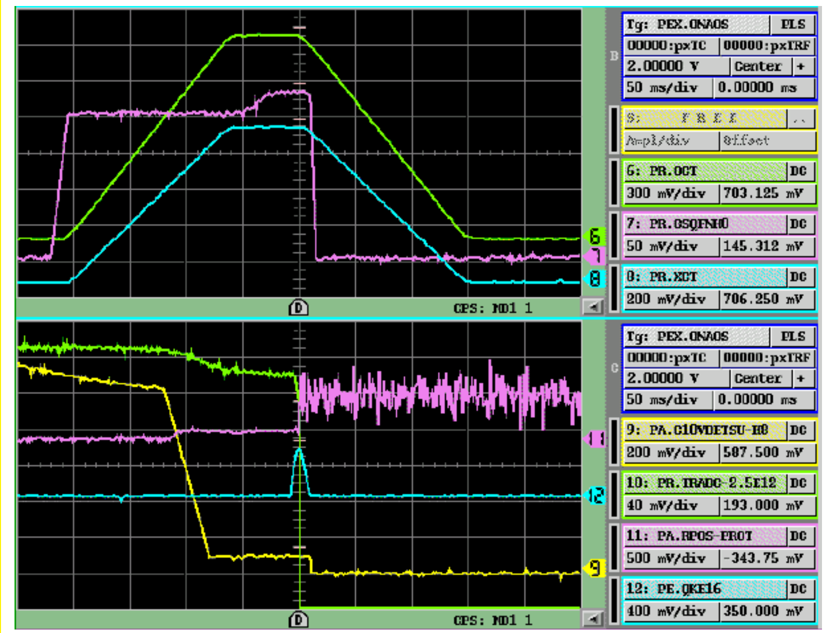


$I_{QSE} = -20$ A; $I_{XCT} = 350$ A;
$I_{OCT} = 690$ A; **Double kick;**

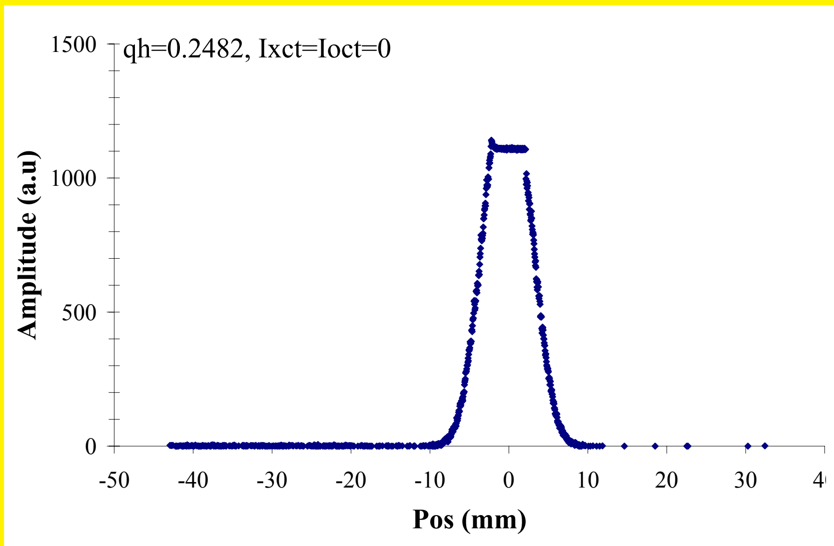
First test of adiabatic capture I

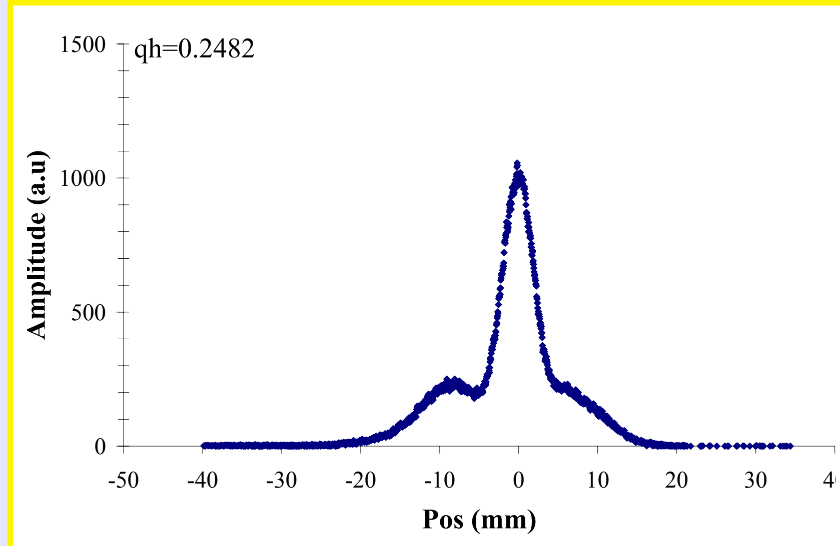
- Beam characteristics:
  - Single bunch.
  - $N_b \approx 5 \times 10^{11}$ p/b.
  - $\epsilon^*_H \approx 12\ \mu$m, $\epsilon^*_V \approx 1.8\ \mu$m.
  - $\Delta p/p \approx 0.4 \times 10^{-3}$.
- The Quadrupoles for varying the machine tune at low energy (**QFOs**) are used in our tests.
- Observations
  - The **rf-voltage is reduced** to decrease the long./transv. coupling during the adiabatic trapping (some **beam losses** are observed during the voltage reduction).
  - **No beam losses** are observed during the slow tune-variation.
  - The **tune value on the second plateau is changed** to test dependence of beam position vs final tune.

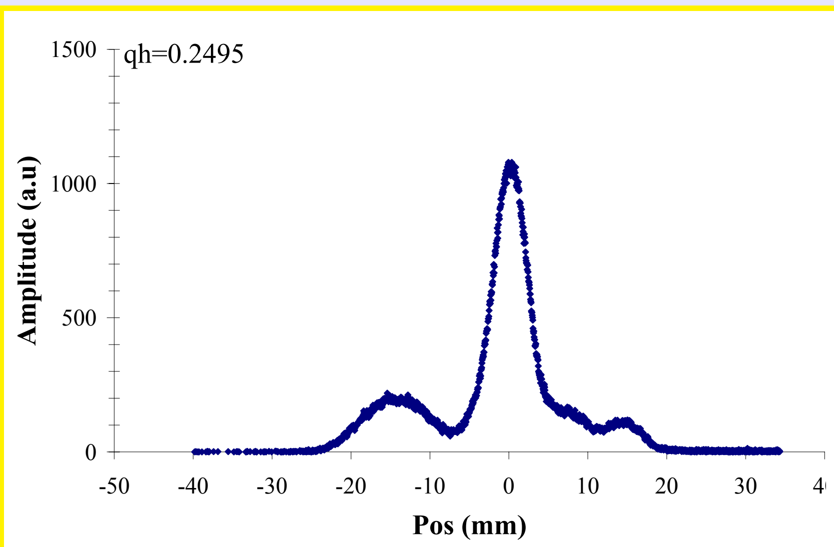
Experimental settings

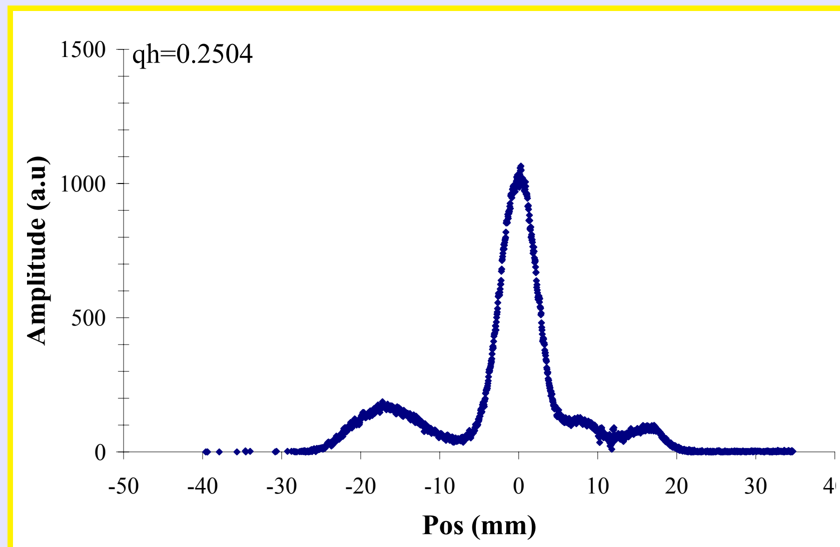


First test of adiabatic capture II

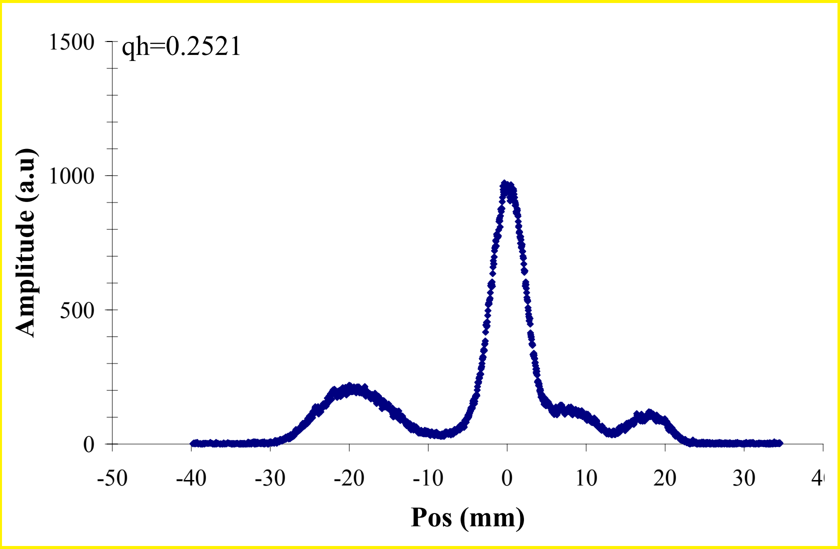


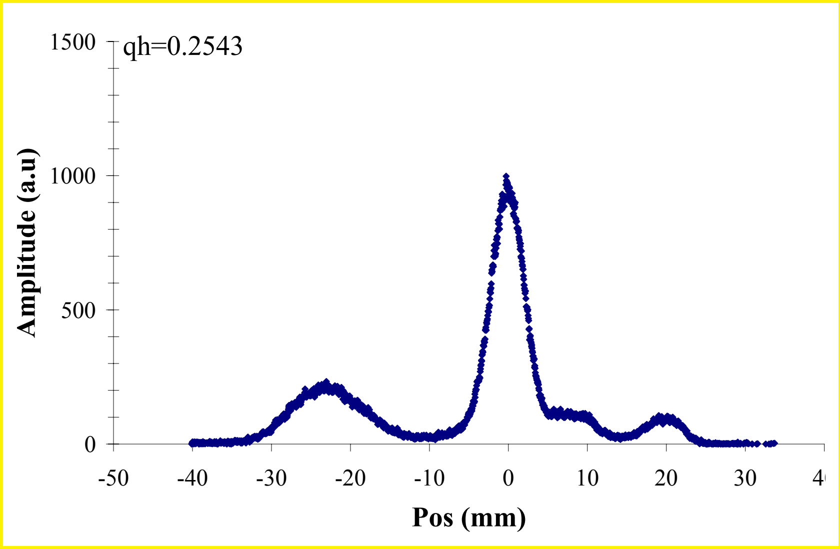


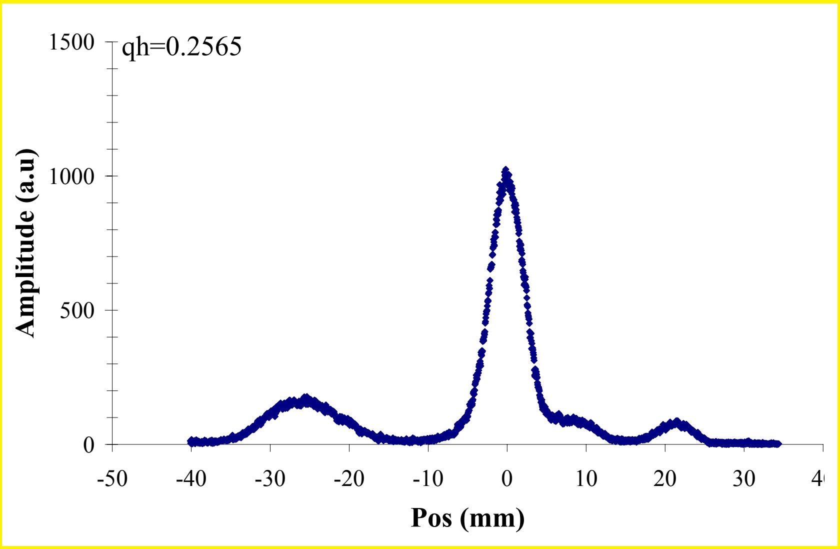


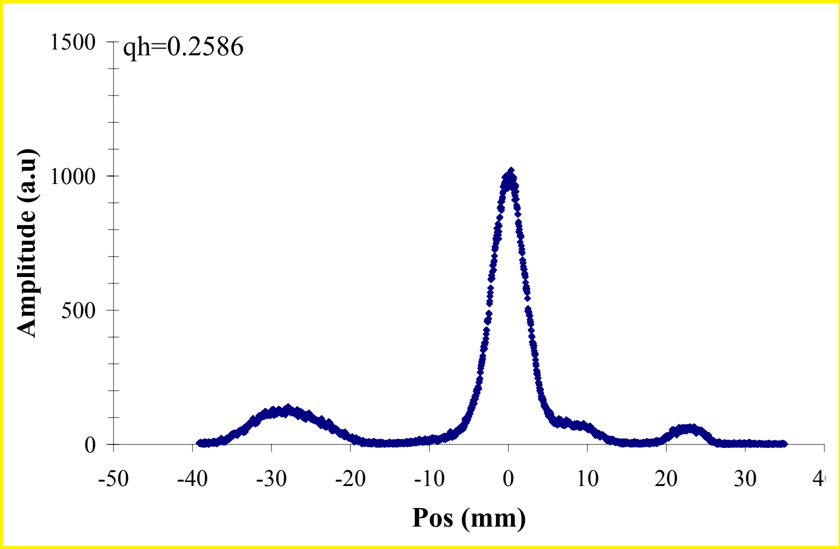


First test of adiabatic capture III









Conclusions and outlook

- **Theoretical predictions** seems to be confirmed by **experimental observations** on the feasibility of **splitting** the beam in the transverse phase space by means of **stable islands**.

- **Further studies** are needed to:

  - Analyse realistic **4D** (**6D**) models.
  - Analyse influence of **space charge** on the process (vital for high-intensity beams).
  - **Quantify relationship** between sextupole, octupole strength and trapped beam parameters (i.e. **emittance**).
  - **Determine adiabatic conditions for trapping**.
  - **Improve capture efficiency** to have same intensity in all the islands.

- **Measurements** are still needed to:

  - **Try extracting the five islands separately**.
  - Use a more realistic beam (**more bunches and more intensity**).